THE PHELIX PULSED POWER PROJECT: BRINGING PORTABLE MAGNETIC DRIVE TO WORLD CLASS RADIOGRAPHY

C. L. Rousculp, W. A. Reass, D. M. Oro, P. J. Turchi, B. J. Hollander, J. R. Griego, R. E. Reinovsky

Los Alamos National Laboratory, PO Box 1663, Los Alamos, NM, USA

Abstract

The PHELIX pulsed power project will introduce magnetically driven hydrodynamics experiments to the Los Alamos National Laboratory's proton radiography facility (pRad). The Precision High Energy-density Liner Implosion eXperiment (PHELIX) has been commissioned at Los Alamos. A small footprint capacitor bank consisting of four parallel connected single-stage marx units (~500 kJ) is cable coupled to a toroidal, current step-up transformer to deliver multi-Mega-Ampere, ~10 μs current pulses to cm size cylindrical loads. In a sequence of tests the performance of each component (capacitor bank and transformer) was evaluated and compared to a circuit model. The transformer coupling was observed to be k ~0.93. The tests culminated in a liner implosion experiment in which an ~3 cm radius, 0.8 mm thick, ~3 cm tall aluminum liner was accelerated to a velocity of ~ 1 km/s. The suite of machine diagnostics included linear Rogowski coils and Faraday rotation for current measurements. The experimental diagnostics include B-dot probes, multi-channel photon Doppler velocimetry (PDV), and single-frame, flash X-radiography to evaluate the performance of the high precision liner implosion. Currently, work is focused on integrating PHELIX into normal operations with the 800 MeV proton radiography facilities. There, high-resolution, high-frame-rate imaging of hydrodynamic experiments will be possible.

I. LANL's Strategic Signature Facility, MaRIE and Proton Radiography

Materials are a central LANL capability. The Matter-Radiation Interactions in Extremes (MaRIE) experimental facility, the first in a proposed new generation of scientific facilities for the materials community, will be used to discover and design the advanced materials needed to meet 21st century national security and energy security challenges. A major theme of MaRIE is to bridge the micron gap. What this means is at atomic scales, static scattering of various diagnostic particles is the norm. At the continuum scale the prevalent diagnostic is some form of imaging. In between there is the micron scale where both scattering and imaging are challenged. However, at this very scale is where microstructure interactions drive continuum properties. For example, dislocations within a lattice and their transport manifest as plastic deformation and yield strength. With MaRIE we will transition from observation and validation to prediction and control [1].

One critical component of MaRIE is the capability to perform high-resolution dynamic radiography. In addition to scattering and nuclear experiments, the Los Alamos Neutron Science Center (LANSCE) is home to a world-class proton radiography (pRad) facility. It is utilizes the 800 MeV proton beam as a diagnostic probe of dynamic experiment. It operates on a six month run cycle each year. Over the course of the past thirteen years, more than 300 dynamic experiments have been imaged at the facility. Figure 1 shows a photo of the inside of the proton radiography facility.

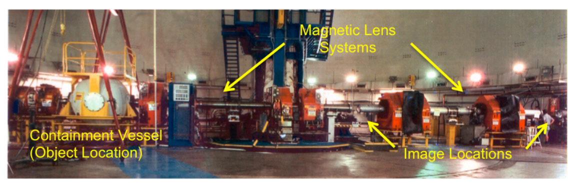

Figure 1. The LANL proton radiography facility at LANSCE. The beam enters from the left, interacts with the object in the containment vessel, and is focused my magnetic lens to two image locations.

LANL pRad utilizes transmission radiography for imaging dynamic experiments. Here, the transmission coefficient is a function of areal density of the material through which the protons pass. A simplified equation takes into account the two predominant factors: multiple coulomb scattering (MCS) and nuclear removal.

$$T(x) = e^{-\frac{x}{\lambda_c}}\left(1 - e^{-\frac{\alpha}{x}}\right) \qquad (1)$$

In Equation 1, x is areal density, λ_c is the MCS length, and α is the nuclear removal factor. This shows that both the thickness and material must be taken into consideration when designing an experiment to be diagnosed with pRad.

LANL pRad is a very high resolution diagnostic. The dynamic range has been shown to be 1-70 g/cm2 as measured in iron. The spatial resolution is ~65 μm FWHM Gaussian for double-line calibration. Temporal

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14. ABSTRACT

The PHELIX pulsed power project will introduce magnetically driven hydrodynamics experiments to the Los Alamos National Laboratorys proton radiography facility (pRad). The Precision High Energy-density Liner Implosion eXperiment (PHELIX) has been commissioned at Los Alamos. A small footprint capacitor bank consisting of four parallel connected single-stage marx units (~500 kJ) is cable coupled to a toroidal, current stepup transformer to deliver multi-Mega-Ampere, ~10 ìs current pulses to cm size cylindrical loads. In a sequence of tests the performance of each component (capacitor bank and transformer) was evaluated and compared to a circuit model. The transformer coupling was observed to be k ~0.93. The tests culminated in a liner implosion experiment in which an ~3 cm radius, 0.8 mm thick, ~3 cm tall aluminum liner was accelerated to a velocity of ~ 1 km/s. The suite of machine diagnostics included linear Rogowski coils and Faraday rotation for current measurements. The experimental diagnostics include Bdot probes, multi-channel photon Doppler velocimetry (PDV), and single-frame, flash X-radiography to evaluate the performance of the high precision liner implosion. Currently, work is focused on integrating PHELIX into normal operations with the 800 MeV proton radiography facilities. There, high-resolution, high-frame-rate imaging of hydrodynamic experiments will be possible.

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varies depending on target. an image is built up by gating individual 5 ns proton packets. 60-100 ns exposure is typical. A movie of 10-30 images is custom tailored to the dynamics of the experiment. There are several other considerations in calculating the expected transmission and resolution of a particular experiment. Here we only mention the effects like detector blur, chromatic aberration, and limbing.

As mentioned above, over 300 dynamic experiments have been performed at pRad. It is worth giving a few examples. For all of these, a similar, approximate-planer geometry it utilized. Here a disk of high explosive (HE) imparts a shock into different targets. It should be pointed out that the strength of the shock is determined by the particular composition of the HE. One advantage of magnetic, pulsed-power drive is that the drive strength can be continuously varied within a range, by the setting the voltage to which the capacitor bank is charged.

The first example of a dynamic material experiment imaged with pRad is the comparison of the spall of various ductile materials. Here a disk is subject to a strong shock. The rarefaction waves meet within the material and put it into such extreme tension that failure occurs and the sample "spalls." Figure 2 shows the pRad images of the spall of various materials. The shock is incident from the bottom into a target disk. In each case a spall scab has dethatched from the sample and is traveling upward away from it.

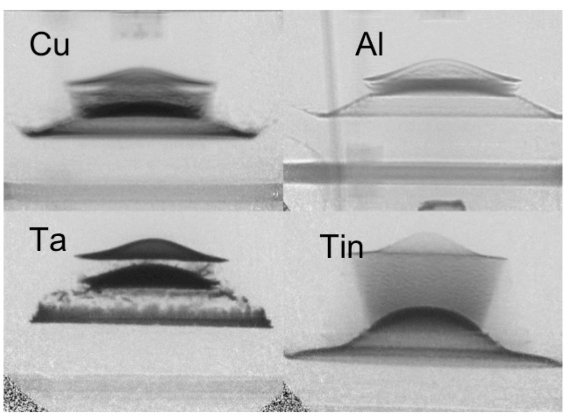

Figure 2. pRad imaging of the spall of various materials.

A second of dynamic material experiment diagnosed with pRad is growth of the Richtmyer-Meshkov instability (RMI). Here a corrugated of specific wave number and amplitude is subject to strong shock loading. The threshold for growth is a function of the product of the two. In Figure 3 the results from a copper sample are shown [2].

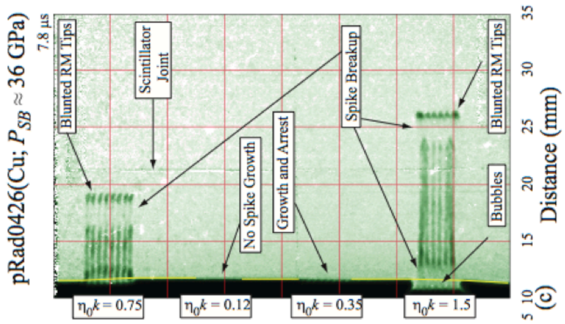

Figure 3. pRad image of RMI threshold for growth. For value of η_0k = 0.12 the growth is suppressed. For value η_0k =0.35 the growth is arrested. For the two cases of η_0k = 0.75 and 1.5, fully developed RMI growth occurs.

As a final example of HE driven, dynamic experiments diagnosed with pRad, there is the study of particulate transport. Here, a thin layer of fine tungsten powder (diam ~ 1 µm) is loaded into an aluminum disk. The shock causes the release of the material into either a vacuum or inert gas atmosphere. Figure 4 shows that the viscous drag of the particles by the inert gas (here argon), causes inhibited transport.

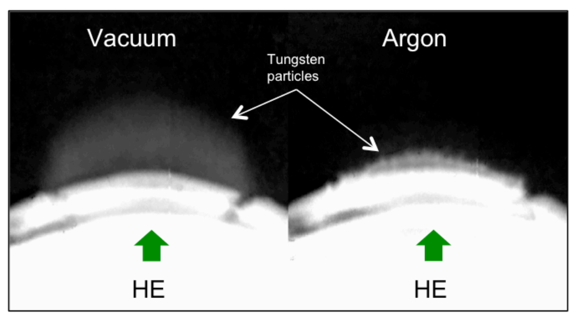

Figure 4. Particulate release experiment imaged with pRAd. Fine tungsten powder is ejected into vacuum (left) and argon (right).

II. PHELIX – Precision High Energy-density Liner Implosion Experiment

In order to provide a driver complementary to HE at pRad, the PHELIX portable pulsed-power driver has been designed and is being constructed. In addition to being able to drive continuum size samples, the main requirement is that it be small and mobile. The whole system has to fit into a 200 ft^2 platform in order to be used at the pRad facility.

It should be pointed out that a pulsed-power driver has several desirable features for dynamic materials experiments. It is naturally cylindrical, which reduces the edge effects in at least one dimension. Since the magnetic field is mass-less and is dissipated by Joule heating, there is no residual stored energy, and thus less chance of

collateral damage. As mentioned before, the drive strength is dial-able via the charge voltage of the capacitor bank. Indeed, a small, portable pulsed-power driver at the multi-frame pRad facility has a distinct economic advantage in rate of data return over a fixed location bank, where only a few frames of imaging can be obtained in a single experiment. Figure 5 shows the conceptual use of pRad to diagnose a pulsed-power driven, liner-on-target experiment.

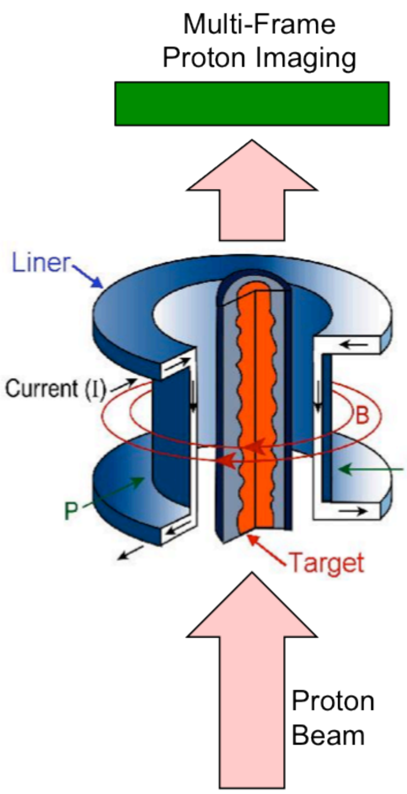

Figure 5. Conceptual use of proton radiography in a pulsed-power, liner-on-target experiment.

The key components and technology of PHELIX are as follows. A two-module, 68 μF, 90 kV, air-insulated marx-modules are cable coupled to a toroidal current step-up transformer. It has a 4:1 winding ratio and a magnetic flux coupling efficiency of k = 0.93. The secondary winding and experimental load has very low inductance. Thus 1 MA peak current in the primary winding produces 4 MA peak current in the secondary winding for driving a liner. In order to not produce too much reverse voltage on the capacitors, reticulated vitreous carbon damping resistors are used on the output headers of each module for a total of 25.1 mΩ of resistance.

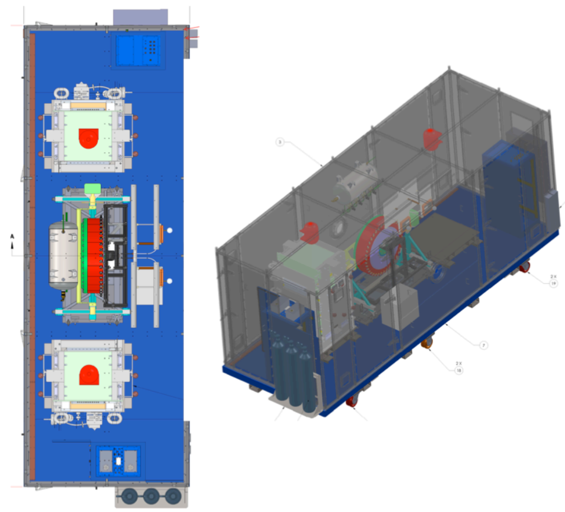

Figure 6. The PHELIX portable pulsed-power driver on a 8' x 25' platform. Two marx modules bracket the toroidal tranformer.

While not portable yet, the PHELIX marx-module, transformer, load system has been extensively tested in the laboratory. The first step was to commission the marx modules. For this a set of 1 m long, shorted cables was attached to each bank. Current viewing transformers and linear Rogowski coils measured the current. The result was a pulse with ~1.5 MA peak current and 6 μs width.

The next step in testing was to connect the marx modules to the transformer and install a static load of 1 nH. A series of shots at voltages 50-84 kV was conducted. Faraday Rotation measured the current in the secondary winding. Figure 7 shows the measured secondary winding current for the 50 kV shot. A peak current of 3 MA and pulse width of 10 μs is observed. The series showed linear dependence of peak current on charge voltage.

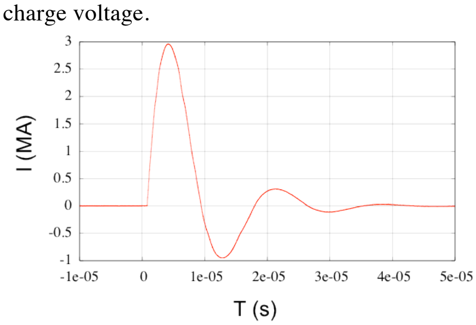

Figure 7. Secondary winding current for the transformer with static load and bank voltage of 50 kV.

The final test of PHELIX was a dynamic liner implosion experiment. Figure 8 shows a cutaway of the liner cassette. The blue piece is a central measuring unit (CMU) with 12 channels of photon Doppler velocimetry (PDV) of the inner surface of the liner. In orange are the heavy copper glide planes. In green is the aluminum return conductor. The inner surface of the liner is in grey.

It is only 0.8 mm thick with 3 cm between the glide planes.

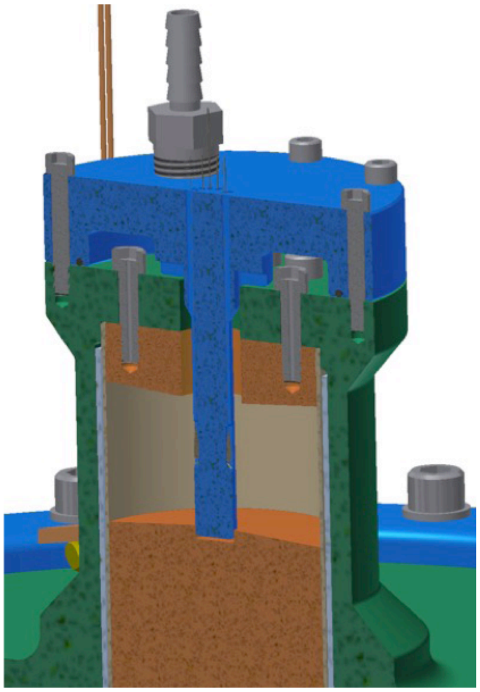

Figure 8. Cutaway of the PHELIX dynamic liner experiment.

A single frame of flash X-radiography captures both the static cassette as well as the dynamic implosion in Figure 9. The liner displays a high degree of both axial and azimuthal symmetry.

The PDV confirms the symmetry. The 12 channels were arrayed at three axial stations (2 at +10 mm from the mid-plane, 2 at -10 mm from the mid-plane, and 8 in the mid-plane). Figure 10 shows the results of the PDV measurements. They show that the liner achieved > 1 km/s velocity.

Figure 9. Flash X-Radiography of the PHELIX liner implosion experiment. The static is on top and the dynamic is below.

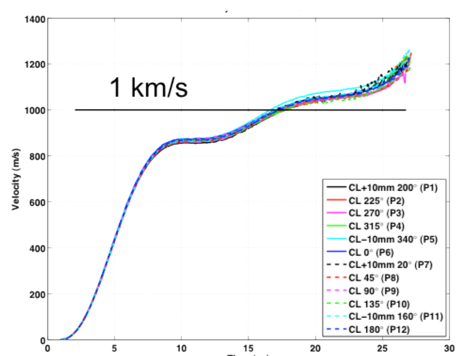

Figure 10. Plot of the 12 Channels of PDV looking at the inside of the liner.

Finally, the Faraday rotation of the secondary-winding/load current is shown in Figure 11. A peak current of 4 MA is shown with a 10 μs pulse width is measured.

III. Summary

The long-term, strategic goal of LANL is a signature facility named MaRIE. There it is envisioned that materials science will move from the paradigm of observation and validation to prediction and control. The existing LANL proton radiography facility with its 800 MeV beam, ~50-100 μm spatial resolution and high

frame-rate imaging will be an integral part of the new facility. The PHELIX portable pulsed power machine will expand the capability of dynamic materials experiments that can be fielded. The first-of-its-kind transformer technology has been tested in the laboratory. A dynamic liner experiment produced a 4 MA peak current with a 10 μs pulse width. The liner was accelerated to > 1 km/s velocity. Flash radiography and multichannel PDV showed a high degree of symmetry.

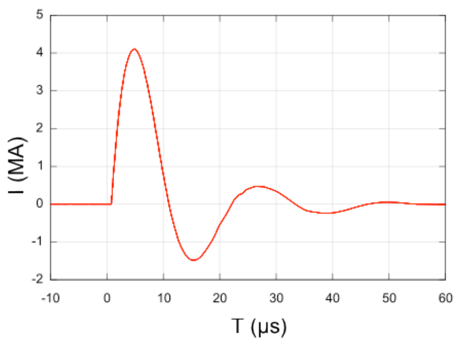

Figure 11. Secondary-winding/load current for the PHELIX dynamic liner experiment.

IV. References

[1] J. Sarrao, "MaRIE: An Experimental Facility Concept Revolutionizing Materials in Extremes," 2010: Available:http://www.lanl.gov/source/projects/marie/index.shtml

[2] F. Merrill, "Proton Radiography Primer," LA-UR-08-07298, 2008.